PHYSICAL REVIEW C **74**, 044901 (2006)

Azimuthal flow of decay photons in relativistic nuclear collisions

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(Received 9 May 2006; revised manuscript received 31 July 2006; published 4 October 2006)

An overwhelming fraction of photons from relativistic heavy-ion collisions has its origin in the decay of π^0 and η mesons. We calculate the azimuthal asymmetry of the decay photons for several azimuthally asymmetric pion distributions. We find that the k_T dependence of the elliptic flow parameter v_2 for the decay photons closely follows the elliptic flow parameter $v_2^{\pi^0}$ evaluated at $p_T \approx k_T + \delta$, where $\delta \approx 0.1$–0.2 GeV, for typical pion distributions measured in nucleus-nucleus collisions at relativistic energies. Similar results are obtained for photons from the 2-γ decay of η mesons. Assuming that the flow of π^0 is similar to those for π^+ and π^- for which independent measurements would be generally available, this ansatz can help in identifying additional sources for photons. Taken along with quark number scaling suggested by the recombination model, it may help to estimate v_2 of the parton distributions in terms of azimuthal asymmetry of the decay photons at large k_T.

DOI: 10.1103/PhysRevC.74.044901 PACS number(s): 25.75.−q, 12.38.Mh

I. INTRODUCTION

The azimuthal flow of particles produced in relativistic heavy-ion collisions has provided a strong evidence for the creation of a hot and dense system very early in noncentral collisions [1]. The importance of this observation stems from the fact that pressure gradients generated in the system at very early times transform the eccentricity in coordinate space for such collisions to the momentum space for distribution of the produced particles [2]. The p_T dependence of the elliptic flow parameter v_2 at lower transverse momenta has been quantitatively explained using hydrodynamics [3]. The observed saturation of v_2 at higher p_T has been attributed to effects of viscosity [4] or incomplete thermalization [5]. The observed scaling of v_2 with the number of valence quarks in the hadrons is understood in terms of the recombination model for hadronization [6,7].

It has recently been suggested that the study of the elliptic flow of thermal photons [8] may provide valuable insight into the buildup of azimuthal flow with time. This will require a subtraction of the contribution of photons from the decay of π^0 and η mesons produced in the collisions [9].

The deviation of elliptic flow of inclusive photons from that of decay photons will thus confirm the presence of additional sources of photons. We shall see later that the elliptic flow of photons from the decay of π^0 and η mesons may also provide useful estimates for v_2 of the partons in the framework of the recombination model.

In the present work, we suggest an ansatz for the evaluation of the elliptic flow of photons from the decay of pions, which could be useful for such studies. In the next section we study the transverse-momentum dependence of the elliptic flow parameter for decay photons for several momentum distribution functions for the π^0 and η mesons. In Sec. III we evaluate the v_2 for photons arising from 2-γ decay of π^0 and η mesons, which are formed from recombination of partons to get a direct relation with v_2 for partons. Finally, we give our conclusions.

II. PHOTONS FROM DECAY OF π^0 AND η MESONS

Consider a π^0 having four-momentum p and mass m decaying into two photons. The momentum distribution of photons in an invariant form is given by [10]:

$$k_0 \frac{dN}{d^3k}(p,k) = \frac{1}{\pi}\,\delta\left(p\cdot k - \frac{1}{2}m^2\right), \tag{1}$$

where k is the four-momentum of the photon.

Thus, the Lorentz invariant cross section for photon production is

$$k_0 \frac{d\sigma}{d^3k} = \int \frac{d^3p}{E}\left(E\frac{d\sigma}{d^3p}\right)\frac{1}{\pi}\,\delta\left(p\cdot k - \frac{1}{2}m^2\right). \tag{2}$$

Let us write the pion distribution as:

$$\frac{d\sigma}{d^2p_T\,dy} = \frac{d\sigma}{2\pi p_T\,dp_T\,dy}\left[1 + 2v_2(p_T)\cos(2\phi) + \ldots\right] \tag{3}$$

for a noncentral collision of identical nuclei, where $v_2(p_T)$ is the momentum-dependent elliptic flow parameter. We consider two typical parameterizations for the pion distribution: an exponential distribution and a power-law distribution. For the first case, we assume

$$\frac{d\sigma}{p_T\,dp_T\,dy} \sim \exp\left(-\sqrt{p_T^2+m^2}/T_0\right) \times \exp(-y^2/2\alpha), \tag{4}$$

where the slope parameter T_0 is of the order of 290 MeV [11] and the width parameter of the rapidity distribution α is taken as $\sim$4. For the power-law distribution, we take [12]

$$\frac{d\sigma}{p_T\,dp_T\,dy} \sim \left(\frac{p_0}{p_0+p_T}\right)^n \times \exp(-y^2/2\alpha), \tag{5}$$

where $p_0 \sim 5$ GeV and n is about 29. The elliptic flow parameter v_2 is approximated as

$$v_2(p_T) = a\left[1 - \exp(-p_t/b)\right], \tag{6}$$

which approximately reflects the increase of v_2 with p_T for lower transverse momenta and saturation of its value at

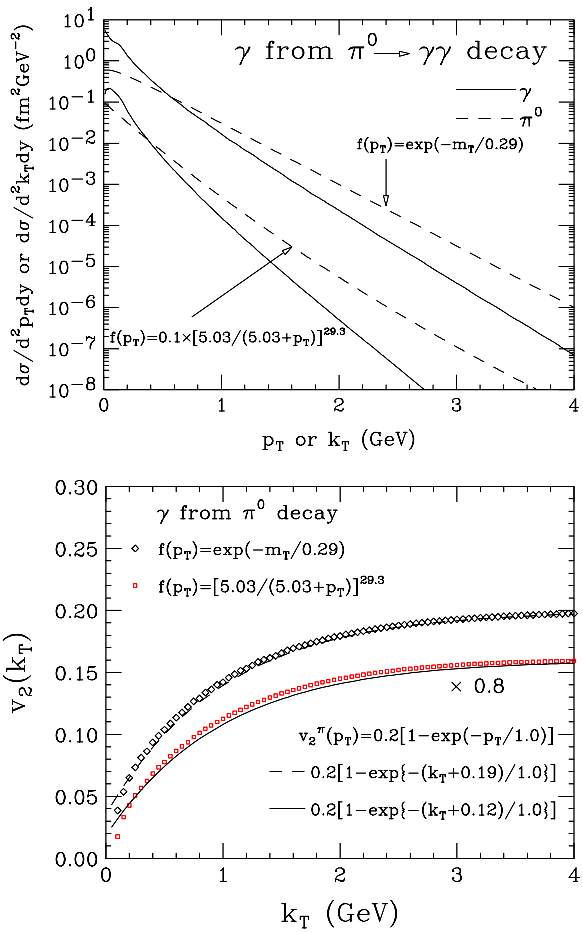

FIG. 1. (Color online) (Upper panel) Spectrum of photons from the decay of π^0 for an exponential [Eq. (4)] and a power-law [Eq. (5)] distribution for pions. (Lower panel) Elliptic flow of photons from decay of π^0 having elliptic flow given by Eq. (6) at $y = 0$. $f(p_T)$ stands for the momentum distribution of the π^0. The symbols give the result of numerical calculation, whereas the curves give the fits.

larger p_T. We have taken $a = 0.2$ and $b = 1$ GeV for the first set of calculations. All the results given in the present work are for photon rapidity equal to zero.

Equation (2) is then evaluated numerically and $v_2(k_T)$ for the resulting photon distribution obtained. In Fig. 1 we give our results for the spectrum of photons from decay of π^0 along with the variation of transverse-momentum dependence of their elliptic flow parameter. We find that for both distributions, the resulting $v_2(k_T)$ for the decay photons can be approximated as:

$$v_2(k_T) \approx v_2^{\pi^0}(p_T), \tag{7}$$

where

$$p_T \approx k_T + \delta \tag{8}$$

and $\delta \approx 0.1$–0.2 GeV, for $k_T > 0.2$ GeV, to an accuracy of better than 1%–3%.

This result can be understood as follows. The δ function in Eq. (1) provides that

$$m_T k_T \cosh(y_p - y_k) - p_T k_T \cos(\phi_p - \phi_k) - \tfrac{1}{2}m^2 = 0, \tag{9}$$

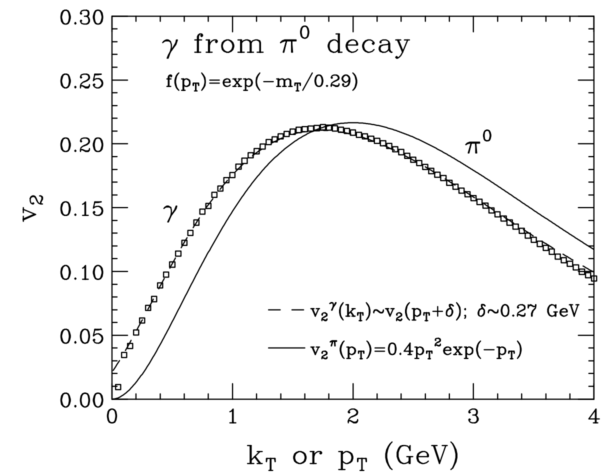

FIG. 2. Elliptic flow parameter for photons from the 2-γ decay of π^0. The symbols denote the calculated v_2, whereas the dashed curve denotes the fit. The $v_2(p_T)$ for pions is taken to rise first, reach a maximum, and drop for larger transverse momenta.

in an obvious notation. Next, we note that once the momentum of the pions is large, the opening angle for the decay photons will be very small [10]. Thus, for example, in the extreme case, we have, $y_p - y_k \approx 0$ and $\phi_p - \phi_k \approx 0$ or π, for the photons that are collinear with the pion. This leads to the following solutions: $k_T \approx p_T$ and $k_T \approx (m^2/4p_T)(1 - m^2/4p_T^2)$ for large p_T.

However, in general, the two photons between them will cover the entire range of the allowed transverse momentum. Both the photons, which will be almost collinear with the pion, will "inherit" the v_2 of the pion, which has a larger transverse momentum. The photon with the lower k_T will, however, be submerged in a much larger yield of photons coming from decay of π^0 having lower p_T, as the transverse-momentum distribution of pions falls steeply with increase in p_T. Thus, in general the v_2 of a photon with a given transverse momentum will be larger than the v_2 of a pion with the same transverse momentum. This accounts for the shift [see Eq. (8)].

This argument will hold even if the $v_2(p_T)$ for the pions decreases with increase in p_T, which is likely for larger p_T. The only difference would be that v_2 for the decay photons will now be smaller than the v_2 for the pions at the same transverse momentum (Fig. 2).

The spectra and the transverse-momentum dependence of the elliptic flow parameter for the η mesons are given in Fig. 3. The rich structure seen for the η mesons at smaller transverse momenta has its origin in the large mass of the η mesons. Thus, we find that the v_2 for decay photons coming from the 2-γ decay of η mesons approaches the v_2 for the mesons only at larger transverse momenta (>0.8–1.0 GeV). For the simple parametrizations of the momenta considered here, v_2 is negative for very low k_T as the decay photons are distributed away from the major axis in the momentum space when the p_T of the η mesons is low and the opening angles are large.

Of course, a more complete analysis would include the photons coming from the 3-π^0 decay of the η mesons, which will mainly populate the low k_T window. Although a simulation of the contribution of this process to the v_2

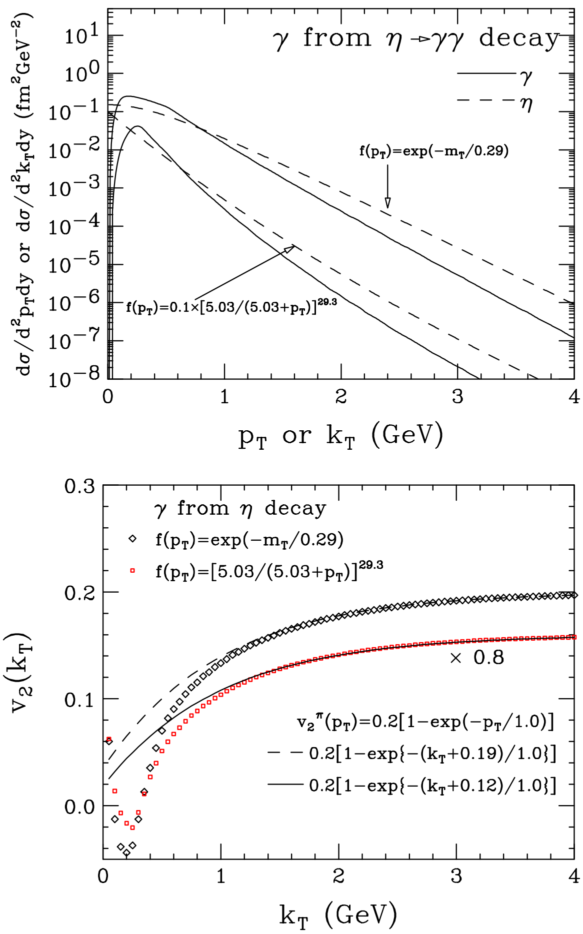

FIG. 3. (Color online) Same as Fig. 1 for η mesons.

can be straightforward using standard event generators, a direct evaluation will not be easy as it would involve a 10-dimensional numerical integration.

However, we can easily make an estimate of the range of the transverse momenta of photons, where the photons arising from decay $\eta \rightarrow 3\pi^0 \rightarrow 6\gamma$ would contribute. The maximum kinetic energy of a π^0 in the rest frame of the η meson is given by [14]:

$$T = \frac{(m_\eta - m_\pi)^2 - 4m_\pi^2}{2m_\eta} \approx 80\,\text{MeV}. \tag{10}$$

Thus, for example, the maximum energy of a pion emerging from an η meson having a momentum of 2 GeV would be of the order of 0.62 GeV and would contribute to photons having momenta less than that. Next, we recall that η/π^0 is of the order of 0.44 for $p_T > 2$ GeV and is expected to drop to zero at $p_T = 0$, at least according to calculations based on PYTHIA [15]. This coupled with the branching ratio of about 0.3 for this mode of decay should ensure that the contribution of photons from the 3-π^0 decay of η mesons would be limited to smaller momenta. A more detailed study of this effect would definitely be useful.

Let us return to the discussion of the v_2 of photons from the 2-γ decay of π^0 and η mesons. We now plot the ratio of the elliptic flow parameters of the calculated decay photons and the mesons as a function of their transverse momenta in Fig. 4. We see once again that v_2 for the two are quite similar when transverse momenta exceeds 1 GeV. Similar results for the transverse-momentum dependence of $v_2^\gamma/v_2^{\pi^0}$ had earlier been noted by the WA98 group [16]. We now understand this in terms of the momentum shift δ [Eq. (8)].

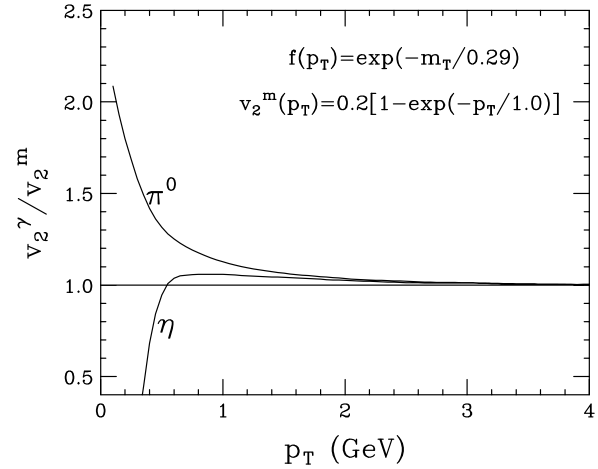

FIG. 4. Transverse-momentum dependence of the ratio of elliptic flow parameters for decay photons and the π^0 or η meson.

Considering the likely usefulness of the relation given by Eq. (8) we have examined it to determine the dependence of δ on the slope-parameter T_0 or the power-law parameter n (see Fig. 5). We see that, in general, the shift δ is smaller if the distribution is steeper. This may be considered as a generalization of the Sternheimer's [13] prescription for azimuthally asymmetric distribution of pions and their decay photons.

We now take a more general shape of the transverse-momentum dependence of the v_2 for pions, which rises with p_T, reaches a maximum and then starts decreasing. We illustrate our discussion (see Fig. 2) by taking

$$v_2(p_T) = 0.4\, p_T^2\, \exp(-p_T)\,. \tag{11}$$

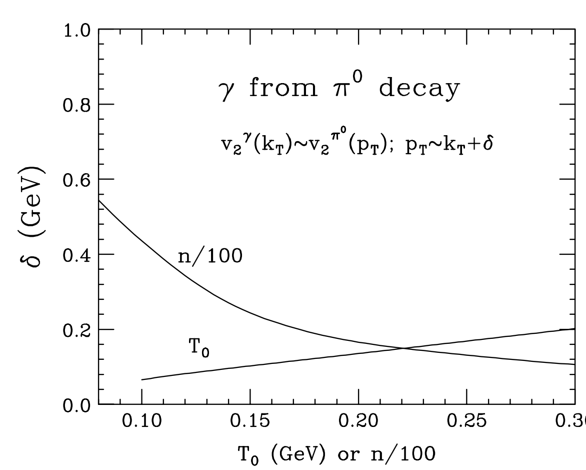

FIG. 5. Variation of the shift parameter δ with the slope parameter (T_0) and the power-law parameter n for the photons coming from the decay of π^0.

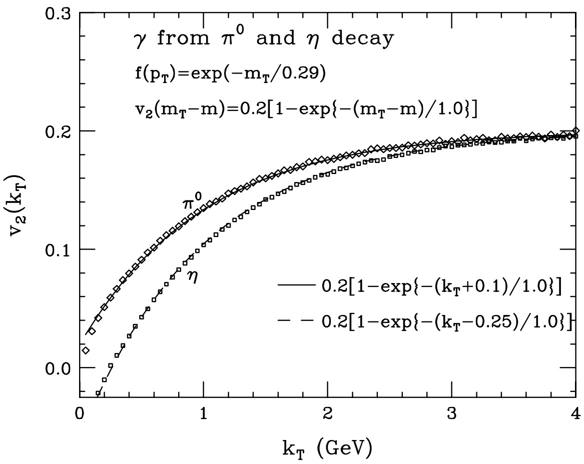

FIG. 6. Elliptic flow parameter for photons from the 2-γ decay of π^0 and η mesons. The hadron v_2 is taken to scale with "transverse kinetic energy" (Ref. [17]). Symbols, as before, denote the calculated values.

We again see that the transverse-momentum dependence of v_2 for the decay photons is obtained from the v_2 for the pions by a shift of about 0.27 GeV.

It has been recently reported [17] that the so-called quark-number scaling of the elliptic flow parameter suggested by the recombination model works much more accurately when plotted in terms of "transverse kinetic energy" or $m_T - m$, where m is the mass of the hadron. To see the consequences of this behavior of the elliptic flow parameter, we now replace p_T with $m_T - m$ in Eq. (6). Next, taking the exponential distribution function [Eq. (4)] for transverse momenta, we calculate the elliptic flow parameter for decay photons from π^0 and η mesons (see Fig. 6).

Identifying k_T of the photons with the so-called "transverse kinetic energy," we again see that v_2 for photons is simply related to v_2 for the pions by a small shift of ≈0.1 GeV in the transverse kinetic energy of π^0. We also find that we can easily describe the v_2 of the photons from the decay of η mesons by a small negative shift.

Thus, we see that the elliptic flow parameter of decay photons from π^0 which make an overwhelming contribution to the inclusive photons in relativistic heavy-ion collisions is simply related [Eq. (8)] to the elliptic flow parameter for π^0. As we can get independent information about the later in terms of the flow of π^+ and π^-, these results could be useful in identifying additional sources of photons [9].

III. RECOMBINATION MODEL AND DECAY PHOTONS

As remarked earlier, one of the more interesting results of elliptic flow studies has been the approximate quark-number scaling of the hadronic v_2. This finds a natural explanation in terms of the recombination model for hadronization of the quark-gluon plasma [6,7], which suggests that in the region of p_T where the recombination of the partons dominates the process of hadronization, that is $p_T < 4(6)$ GeV for mesons (baryons) and the effect of mass is minimal, v_2 obeys a simple scaling law:

$$v_2(p_T) \approx n v_2^q(p_T/n), \tag{12}$$

where n is the number of valence quarks in the hadron and v_2^q is the elliptic flow parameter for them.

The shifted scaling of the v_2 of the decay photons with the v_2 for the π^0 and η seen earlier for a variety of momentum distributions and momentum dependences of v_2, taken along with the valence-quark scaling of the v_2 for hadrons, holds out the promise of the "lowly" decay photons providing a direct measure of the v_2^q of the partons. To examine this possibility, we now explicitly calculate the v_2 for photons from the decay of π^0 and η, which in turn, are formed by the recombination of partons.

The transverse-momentum distribution of mesons formed by the recombination from thermal parton distribution can be written as [7]:

$$\frac{dN}{d^2p_T dy}(y=0) \sim K_1\left[\frac{2\left(m_q^2 + p_T^2/4\right)^{1/2}\cosh\eta_T}{T}\right] \times m_T I_0\left[\frac{p_T \sinh\eta_T}{T}\right]. \tag{13}$$

In the above m_T is the transverse mass of the hadron, $m_q = 260$ MeV is the quark mass, $T = 175$ MeV is the transition temperature, and η_T is the transverse rapidity such that $\tanh\eta_T = 0.55$, appropriate for a system created in collision of gold nuclei at $\sqrt{s_{NN}} = 200$ GeV. While writing the above we have utilized the δ function for the asymptotic form of the perturbative meson distribution amplitude.

We now return to the present calculation. In these illustrative studies, we account for the elliptic flow of the mesons by multiplying the above distribution with $[1 + 4v_2^q(p_T/2)\cos(2\phi)]$. We have calculated $v_2^q(p_T)$, the elliptic flow for the partons, using Eq. 81 of Fries *et al.* [7].

In Fig. 7, we give our results for the elliptic flow parameter for pions obtained, using the recombination model along with the v_2 for the photons coming from the decay. We should not take the results for the v_2 for pions for lower p_T too literally,

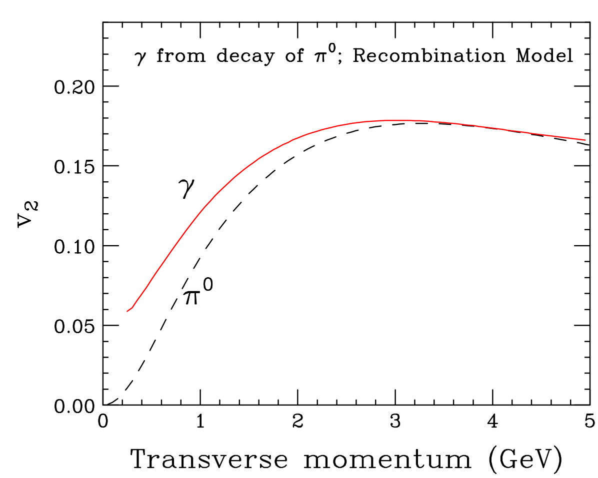

FIG. 7. (Color online) Elliptic flow parameter for photons (solid curve) from the decay of π^0 (dashed curve) obtained using the recombination model.

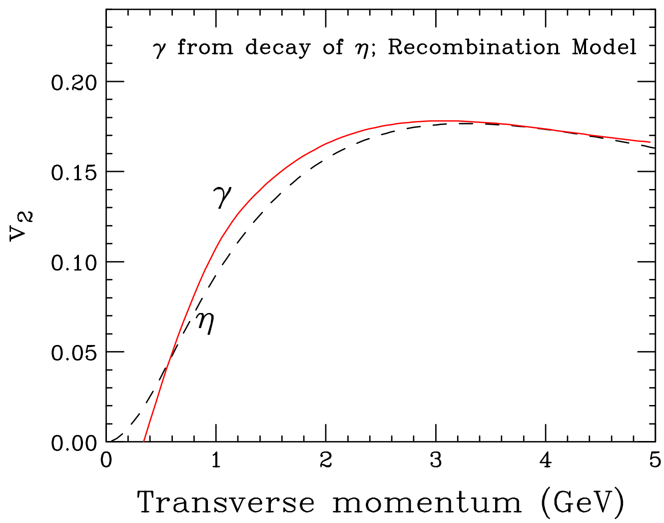

FIG. 8. (Color online) Elliptic flow parameter for photons (solid curve) from the 2-γ decay of η mesons (dashed curve) obtained using the recombination model.

as the pion mass is much smaller than $2m_q$, which goes into making it. However, for larger p_T this difference is not very relevant and we can trust the model. We see that v_2^γ closely follows the v_2^π as before.

The mass of η mesons, however, is large enough to be free from this complication. We see that, once again, the decay photons closely follow the azimuthal asymmetry of the η mesons at larger p_T (see Fig. 8).

IV. SUMMARY

We have studied the azimuthal asymmetry of distribution of photons originating from the 2-γ decay of π^0 and η mesons produced in relativistic heavy-ion collisions. Several distribution functions and parametrizations of the transverse-momentum dependence of the elliptic flow parameter, including those coming from the recombination model, have been considered.

We have empirically found that the elliptic flow parameter for the photons from the decay of pions is quite close to the same for the pions evaluated at a transverse momentum shifted by about 0.1–0.2 GeV. This has its origin in the small opening angle for the photons for pions having large momenta. Similar results are found for photons from the 2-γ decay of η mesons, at $p_T > 1$ GeV.

These empirical findings could be useful in identifying additional sources of photons, as the elliptical flow of π^0 should be similar to that for π^+ and π^-. The flow of η mesons could perhaps be approximated with those for kaons based on considerations of their masses and the number of valence quarks. In any case, in general, the yield of η mesons is much less compared to that for pions. Thus the presence of an additional source of photons will be indicated by the deviation of the v_2 for inclusive photons from the v_2 of decay photons from the 2-γ decay of π^0 and η mesons, which could be obtained using the v_2 for charged pions and kaons.

We add that a relation [18] between the p_T integrated anisotropy for π^0 and photons from its decay, obtained using simulations, has been successfully used to analyze the azimuthal anisotropy of decay photons in the WA98 experiment [19]. Thus, an experimental verification of the empirical findings for the transverse-momentum dependence of the elliptic flow reported in the present work may be of considerable interest. In general, such a study would also account for the acceptance and efficiency of the photon detectors, which is beyond the scope of this work.

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